Physiography, Geology, and Land Cover of Four Watersheds in Eastern Puerto Rico

By Sheila F. Murphy, Robert F. Stallard, Matthew C. Larsen, and William A. Gould

Chapter A of

Water Quality and Landscape Processes of Four Watersheds in Eastern Puerto Rico

Edited by Sheila F. Murphy and Robert F. Stallard

Professional Paper 1789–A

U.S. Department of the Interior
U.S. Geological Survey

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Abbreviations Used in This Report

cm	centimeter
km	kilometer
km^2	square kilometer
m	meter
mm	millimeter
Ma	mega-annum, 1 million years old
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WEBB	Water, Energy, and Biogeochemical Budgets

Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Physiography, Geology, and Land Cover of Four Watersheds in Eastern Puerto Rico

By Sheila F. Murphy,[1] Robert F. Stallard,[1] Matthew C. Larsen,[2] and William A. Gould[3]

Abstract

Four watersheds with differing geology and land cover in eastern Puerto Rico have been studied on a long-term basis by the U.S. Geological Survey to evaluate water, energy, and biogeochemical budgets. These watersheds are typical of tropical, island-arc settings found in many parts of the world. Two watersheds are located on coarse-grained granitic rocks that weather to quartz- and clay-rich, sandy soils, and two are located on fine-grained volcanic rocks and volcaniclastic sedimentary rocks that weather to quartz-poor, fine-grained soils. For each bedrock type, one watershed is covered with mature forest, and the other watershed, like most of Puerto Rico, has transformed from relatively undisturbed pre-European forest to intensive agriculture in the 19th and early 20th centuries, and further to ongoing reforestation that began in the middle of the 20th century. The comparison of water chemistry and hydrology in these watersheds allows an evaluation of the effects of land-use history and geology on hydrologic regimes and erosion rates. This chapter describes the physiography, geology, and land cover of the four watersheds and provides background information for the remaining chapters in this volume.

Introduction

Five field sites across the nation are being monitored long-term as part of the U.S. Geological Survey's (USGS) Water, Energy, and Biogeochemical Budgets (WEBB) program (Baedecker and Friedman, 2000). The Puerto Rico WEBB site, located in eastern Puerto Rico, represents a montane, humid-tropical environment. Its geology and land cover are typical of large regions of the humid tropics, particularly montane regions that are affected by hurricanes (Larsen and Stallard, 2000). The Puerto Rico WEBB project has been evaluating hydrological, chemical, and sediment budgets and processes in four watersheds of differing geology and land use in eastern Puerto Rico since 1991 (Larsen and others, 1993). Two watersheds are located on coarse-grained granitic rocks, and two are located primarily on a combination of fine-grained volcanic and volcaniclastic sedimentary rocks. For each bedrock type, one watershed is covered with mature forest, and the other watershed has been affected by agricultural land use typical of eastern Puerto Rico. The comparison of water chemistry and hydrology in these watersheds allows an evaluation of the effects of land-use history and geology on hydrologic regimes and erosion rates.

This chapter describes and compares the physiography, geology, soils, vegetation, and land cover of the watersheds. Climate and hydrology are described in Murphy and Stallard (2012), land-cover change is discussed in Gould and others (2012), and erosional processes are described in Larsen (2012). These comparisons provide context for data presented in the remaining chapters.

Site Description

Puerto Rico is a 9,000-square kilometer (km^2) island within the Greater Antilles, located about 1,700 km southeast of Miami, Fla., at about latitude 18°N., longitude 66°W. (fig. 1). The WEBB study watersheds discussed here and in other chapters of this professional paper are gaged subwatersheds of larger watersheds having the same name. The Mameyes (17.8 km^2) and Icacos (3.26 km^2) watersheds are located inside El Yunque National Forest, a 113-km^2 forest preserve administered by the U.S. Department of Agriculture (USDA) Forest Service. El Yunque National Forest is conterminous with the Luquillo Experimental Forest (fig. 1), which has been the site of a National Science Foundation Long-Term Ecological Research project since 1985, and it is designated an International Biosphere Reserve by the United Nations Educational, Scientific, and Cultural Organization. The Cayaguás (26.4 km^2) and Canóvanas (25.5 km^2) watersheds are located within the partially urbanized, agriculturally developed yet reforesting, Río Grande de Loíza watershed (fig. 1).

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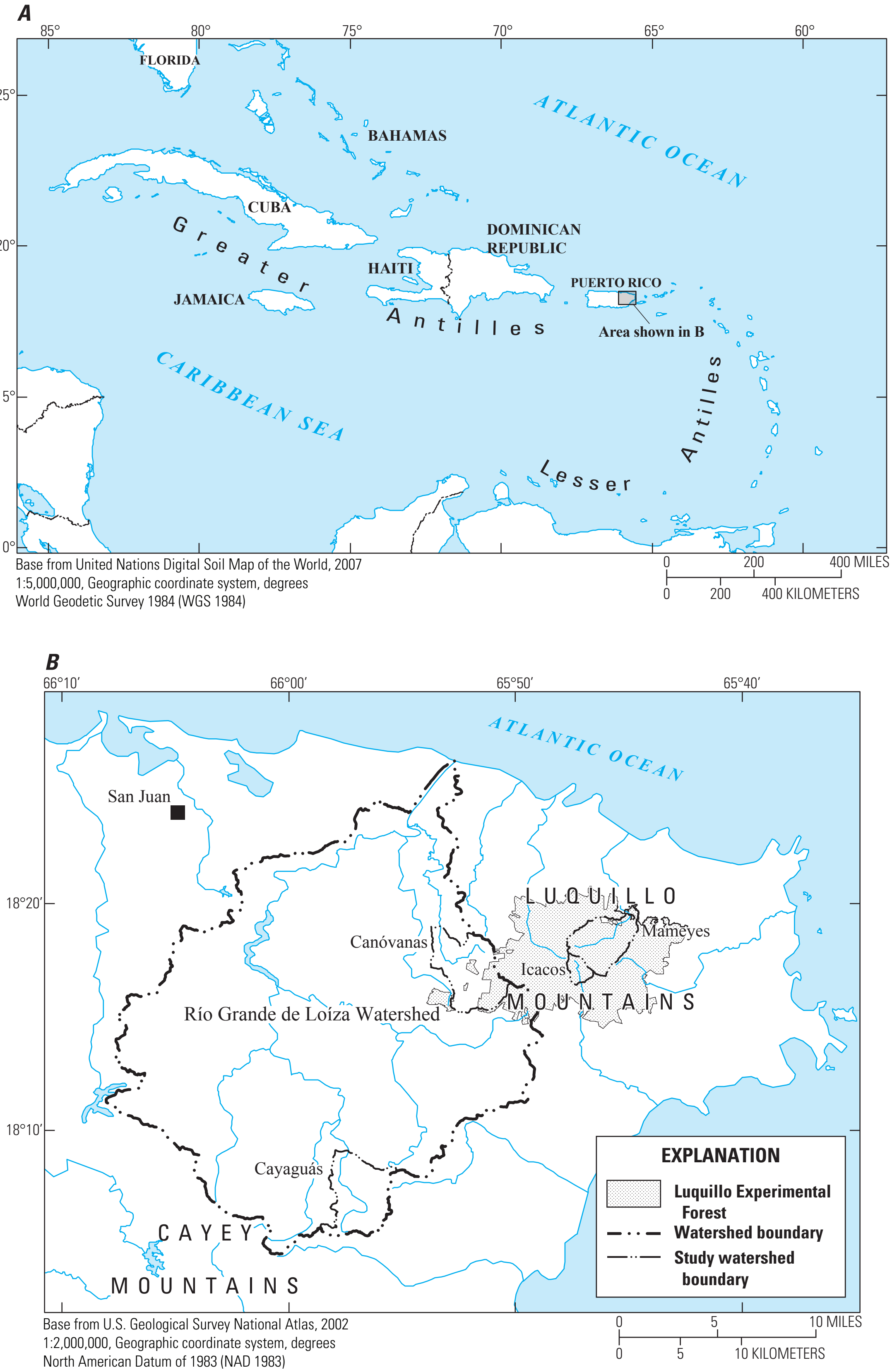

Figure 1. Location of Puerto Rico and study watersheds, eastern Puerto Rico.

Physiography

Puerto Rico is mountainous with central highlands surrounded by flat-lying coastal plains and alluvial valleys (fig. 2). Mountain ranges generally are oriented east-west and dominate the southern two-thirds of the island. Stream channels are steep, and most river valleys are deeply incised. Accelerated weathering in the north-facing watersheds, compared with the slower weathering on the drier southern slopes, has shifted the divide south such that streams are longer and their slopes are gentler on the north side of the island than on the south (Ramos-Ginés, 1999).

The Mameyes, Icacos, and Canóvanas watersheds drain the rugged Luquillo Mountains (fig. 2). The Mameyes watershed is located on the eastern side of the Luquillo Mountains (fig. 3). Slopes in this watershed mostly face north, northeast, and east (fig. 4), directly into the dominant east and northeast wind directions (Calvesbert, 1970). The Canóvanas watershed is on the western side of the Luquillo Mountains, with southwest to northwest aspects, facing away from prevailing winds. Relief in the Mameyes and Canóvanas watersheds is almost 1,000 meters (m) (table 1). The smaller Icacos watershed is located at elevations between about 620 and 832 m, and slopes typically face east, southeast, and southwest (fig. 4). A ridge approaching 800 m elevation separates the Icacos and Mameyes watersheds. Five peaks are higher than 1,000 m in the Luquillo Mountains (U.S. Geological Survey, 1967); the highest, El Toro (1,075 m), is located between the Icacos and Canóvanas watersheds (fig. 3). The Cayaguás watershed, located southwest of the Luquillo Mountains, consists of low hills and alluvial valleys; the Cayey Mountains are located to the west (fig. 2). Slopes in the Cayaguás watershed show no predominant orientation (fig. 4). Hillslopes and channels are steep in all of the WEBB watersheds, and mean hillslopes range from 0.189 (10.7°) in the Cayaguás watershed to 0.365 (20.0°) in the Mameyes watershed (table 1).

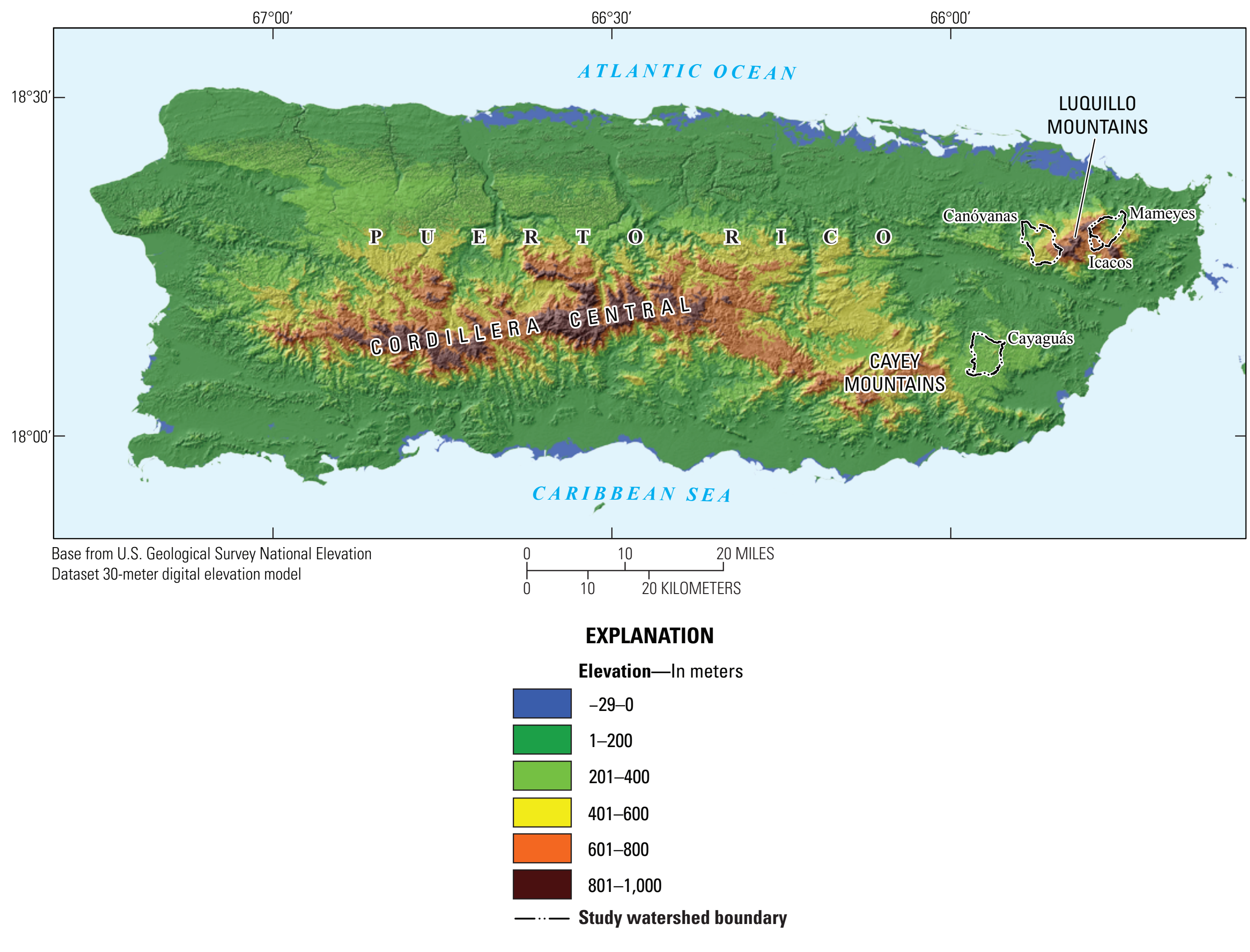

Figure 2. Elevation and relief of Puerto Rico, showing major mountain ranges and study watersheds (outlined).

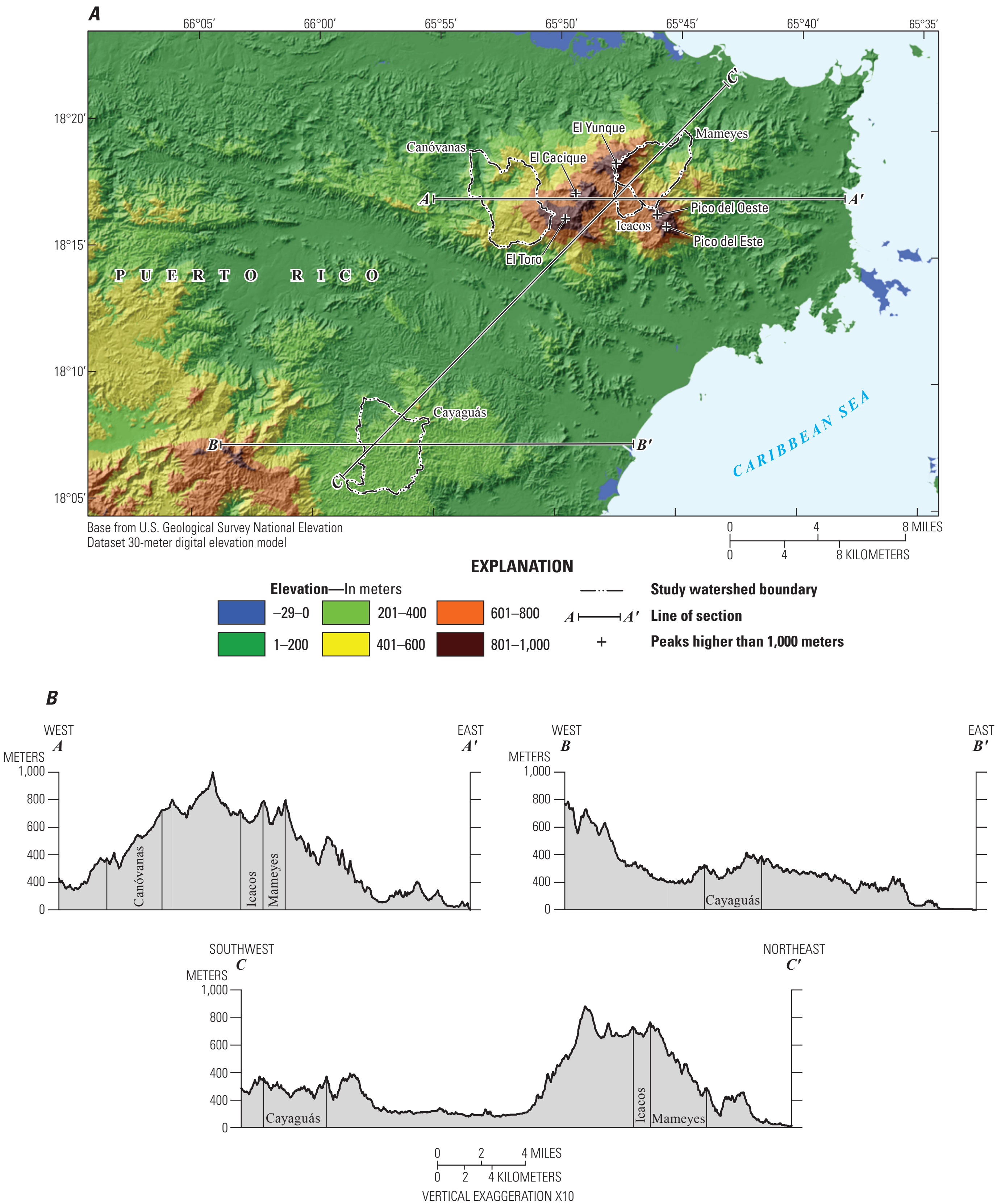

Figure 3. *A*, Elevation and relief of eastern Puerto Rico, showing study watersheds (outlined), and three lines of cross section; *B*, elevation profiles along lines of cross section.

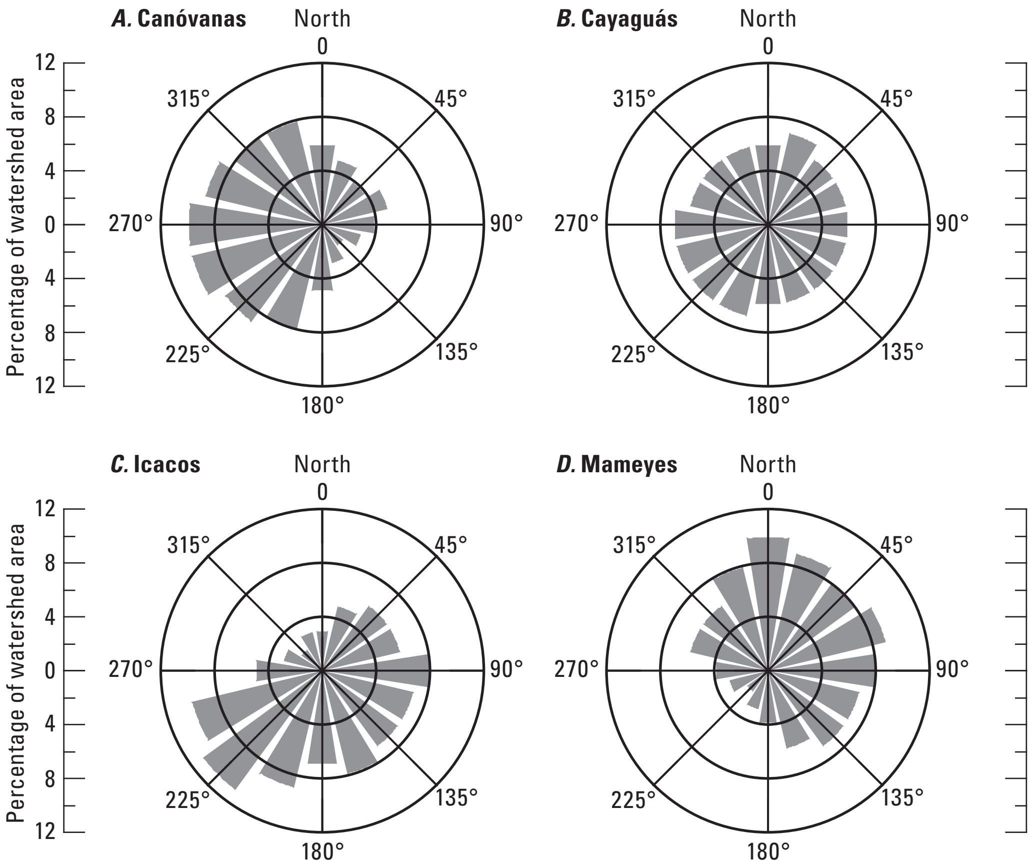

Figure 4. Percentage of watershed area with each aspect, Canóvanas, Cayaguás, Icacos, and Mameyes watersheds (determined from elevation data from U.S. Geological Survey).

Table 1. Geomorphic and geographic characteristics of study watersheds.

[Values calculated from geographic information system data unless otherwise noted. Slope values are dimensionless]

Characteristic	Icacos	Mameyes	Canóvanas	Cayaguás
Area, square kilometers[1]	3.26	17.8	25.5	26.4
Minimum elevation, meters	620	83	70	156
Maximum elevation, meters	832	1,050	956	445
Mean elevation, meters	686	508	464	287
Mean hillslope of watershed[2]	0.222	0.365	0.255	0.189
Mean channel slope[2]	0.073	0.21	0.151	0.12
Main channel length, kilometers[2]	2.01	13.6	21.33	23.5
Total channel length, kilometers[2]	2.91	24.02	34.37	49.46
Dominant bedrock type	Granitic	Volcaniclastic	Volcaniclastic	Granitic
Dominant land use history	Forest	Forest	Agricultural	Agricultural

[1]Díaz and others (2004).

[2]Larsen (1997).

Geology

Puerto Rico is a volcanic island-arc terrain with a geologic record spanning about 150 million years (Bawiec, 1998). It was formed by volcanism and sedimentation characteristic of tectonically active plate boundaries, and it consists of a core of volcanic and plutonic rocks surrounded by younger sedimentary rocks. The WEBB watersheds overlie igneous rocks typical of island-arc terrains. The Luquillo Mountains and the Loíza watershed are underlain largely by marine-deposited volcaniclastic rock with intrusions of granitic rock (figs. 5 and 6; Broedel, 1961; Seiders, 1971a,b,c; M'Gonigle, 1978, 1979; Rogers and others, 1979; Bawiec, 1998). Folding and large-scale strike-slip faulting have deformed strata, resulting in westerly dips such that strata grow progressively younger toward the northwest (Jolly and others, 1998).

Geology in Watersheds Dominated by Volcaniclastic Rock

The Mameyes and Canóvanas watersheds are underlain primarily by Cretaceous, marine-deposited, quartz-poor volcaniclastic rocks. The bedrock of the Mameyes watershed is primarily Fajardo, Tabonuco, and Hato Puerco Formations (41, 38, and 3 percent of the watershed, respectively; another 18 percent of the watershed is underlain by the Río Blanco quartz diorite intrusion, discussed in the next section). The Canóvanas watershed is almost entirely underlain by the Hato Puerco and Lomas Formations (87 and 12 percent, respectively; fig. 6, table 2). The oldest of these formations, the Fajardo Formation, is about 105 to 100 million years old (Ma) (Jolly and others, 1998). Its lithology varies substantially and it has been divided into several members (Briggs, 1973; Briggs and Aguilar-Cortés, 1980).

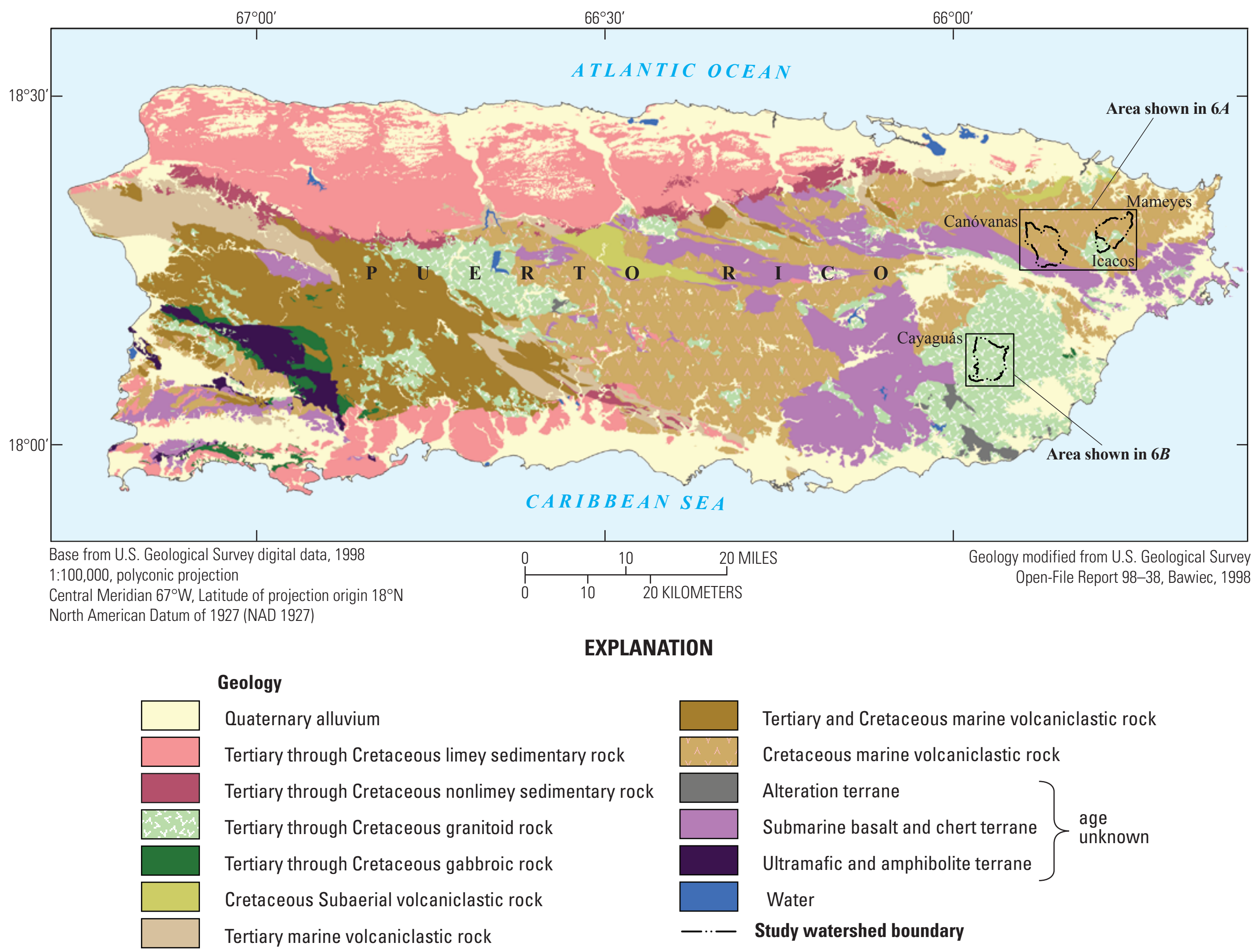

Figure 5. Generalized geology of Puerto Rico (from Bawiec, 1998); study watersheds outlined.

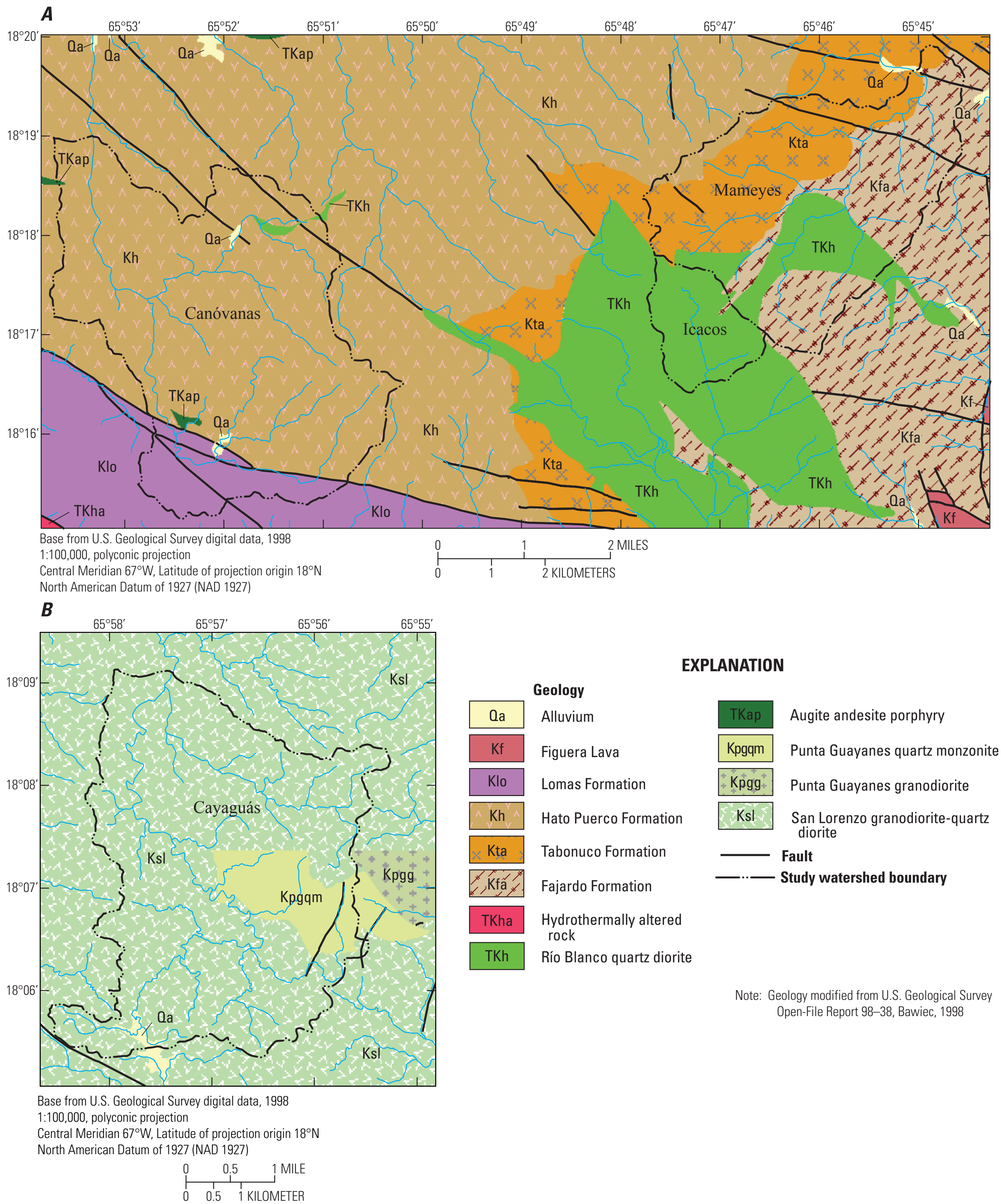

Figure 6. Detailed geology of study watersheds, eastern Puerto Rico (from Bawiec, 1998).

Table 2. Geology of study watersheds, eastern Puerto Rico.[1]

Watershed and formation	Symbol	Rock type	Percent
Canóvanas			
Hato Puerco Formation	Kh	Volcaniclastic	87.2
Lomas Formation	Klo	Volcaniclastic	11.5
Río Blanco quartz diorite	TKh	Intrusive	0.5
Alluvium	Qa	Alluvium	0.4
Augite andesite porphyry	Tkap	Intrusive	0.3
Cayaguás			
San Lorenzo granodiorite-quartz diorite	Ksl	Intrusive	88.0
Punta Guayanes quartz monzonite	Kpgqm	Intrusive	11.3
Alluvium	Qa	Alluvium	0.6
Punta Guayanes granodiorite	Kpgg	Intrusive	0.02
Icacos			
Río Blanco quartz diorite	TKh	Intrusive	98.5
Fajardo Formation	Kfa	Volcaniclastic	1.2
Tabonuco Formation	Kta	Volcaniclastic	0.4
Mameyes			
Fajardo Formation	Kfa	Volcaniclastic	40.9
Tabonuco Formation	Kta	Volcaniclastic	37.9
Río Blanco quartz diorite	TKh	Intrusive	17.8
Hato Puerco Formation	Kh	Volcaniclastic	3.3
Alluvium	Qa	Alluvium	0.04

[1]Adapted from Bawiec (1998).

Thick-bedded tuff breccias, with large clasts of andesite, dominate. They are interbedded with coarse-grained tuff, tuffaceous sandstone, and black cherty siltstone. The Fajardo Formation is largely noncalcareous, except for sporadic calcareous sandstone and siltstone beds and calcareous tuffs (Briggs, 1973).

The Fajardo Formation grades into the overlying Tabonuco Formation, which is about 100 Ma (Jolly and others, 1998). It contains more mudstone and less very thick bedded sandstone and breccia than the Fajardo Formation (Seiders, 1971b). About 60 percent of the Tabonuco Formation consists of volcanic sandstones, which are usually light gray, calcareous, moderately sorted, and fine to very coarse grained, and which are composed primarily of angular volcanic rock fragments and subordinate plagioclase, clinopyroxene, and rare quartz grains (Seiders, 1971b). About 30 percent of the Tabonuco Formation consists of dark gray, thin-bedded to rarely thick-bedded, laminated mudstones, which can be slightly to highly calcareous. About 10 percent of the Tabonuco Formation consists of volcanic breccia and conglomerate.

The Hato Puerco Formation overlies the Tabonuco Formation and is about 97 to 90 Ma (fig. 6; Jolly and others, 1998). More than half of the formation is composed of andesitic to basaltic volcanic sandstone, which contains volcanic lithic clasts, grains of plagioclase, clinopyroxene, and hornblende, and sparse grains and boulders of limestone (Seiders, 1971a). About 30 to 40 percent of the formation consists of volcanic breccias that contain angular to subrounded pieces of andesite or basalt, with fragments of limestone that can make up as much as 30 percent of the breccia. Calcareous mudstone and andesitic to basaltic porphyritic lava are present in minor amounts. The Hato Puerco contains more carbonate material than the Fajardo or Tabonuco Formations, particularly in the vicinity of the Río Canóvanas stream channel, where outcrops of calcareous shales and tuffaceous limestone are common (Meyerhoff, 1931; Seiders, 1971a). Calcareous rocks require relatively small outcrop areas to have a marked effect on stream chemistry (Stallard, 1995), and the larger amount of carbonate rocks in the Canóvanas watershed compared with the Mameyes watershed is reflected in stream chemistry (Stallard and Murphy, 2012).

The Lomas Formation, found in the southern part of the Canóvanas watershed, consists of gray-green, thick-bedded, poorly sorted andesitic to basaltic volcanic breccia and sandstone, with minor pillow lava locally (Seiders, 1971c). Strata commonly contain pumice, vesicular lava fragments, and grains of plagioclase and clinopyroxene, and calcite is locally abundant in the matrix (Seiders, 1971c). This formation is seen at the surface only in fault blocks and is not observed in depositional contact with other formations; on the basis of its similarities with other formations in the region, it has been estimated to be between 90 and 85 Ma (Jolly and others, 1998).

The intrusion of the Río Blanco quartz diorite (discussed in the next section) metamorphosed the Fajardo, Tabonuco, and Hato Puerco Formations within a 2–4 km contact zone (Bawiec, 1998), resulting in rocks that are typically harder; the divide between the Mameyes and Icacos watersheds was formed on the slightly hardened rocks of the metamorphic aureole. In the metamorphosed rocks, hornblende, garnet, epidote, chlorite, iron sulfide minerals, gold, copper, and quartz, and aplitic veins have been identified (Seiders, 1971a,c; Bawiec, 1998). Gold-, silver-, and copper-bearing deposits were first worked by the Spanish in the early 1600s; production was limited to several small adits within the contact zone (Wadsworth, 1970; Cardona, 1984; Bawiec, 1998). Placer gold from weathered metamorphosed rocks was mined intermittently in the Mameyes and Loíza watersheds beginning in the 1500s.

Geology in Watersheds Dominated by Granitic Rock

The Icacos and Cayaguás watersheds are primarily underlain by Upper Cretaceous and Tertiary granitic rocks. Almost all (99 percent) of the Icacos watershed is underlain by the Río Blanco quartz diorite (fig. 6, table 2), which intruded the surrounding volcaniclastic rocks about 49 to 42 Ma (Smith and others, 1998). The Río Blanco quartz diorite is light-gray, medium- to coarse-grained, and commonly contains plagioclase, quartz, amphibole, and minor biotite in a fine- to medium-crystalline groundmass of quartz, amphibole, orthoclase, and plagioclase, and with accessory zircon, tourmaline, sphene, and epidote (Seiders, 1971a,b; table 3). Plagioclase ranges from fresh to sericitized. Hornblende is commonly altered to chlorite, calcite, and epidote (Seiders, 1971a). Biotite is commonly fresh, but it is also altered to chlorite (Murphy and others, 1998). In some areas the Río Blanco quartz diorite contains pyrite, molybdenite, or disseminated chalcopyrite (Bawiec, 1998).

About 88 percent of the Cayaguás watershed is underlain by the San Lorenzo granodiorite–quartz diorite intrusion (fig. 6, table 2), which has been dated to be about 73 Ma (Rogers and others, 1979; Bawiec, 1998). This intrusion occupies a 500-km² area in southeastern Puerto Rico. It is a medium- to dark-gray, granitic-textured, medium-crystalline, generally massive granodiorite which grades into quartz diorite and locally into quartz monzonite. It is composed generally of plagioclase, potassium feldspar, quartz, hornblende, and minor biotite and accessory magnetite, sphene, apatite, and zircon (Rogers and others, 1979) (table 3). Many plagioclase grains are partly sericitized and argillized. Hornblende is commonly altered to chlorite and epidote, and biotite is commonly altered to chlorite.

About 11 percent of the Cayaguás watershed has been mapped as Punta Guayanes quartz monzonite, which has been dated at about 66 Ma (Rogers and others, 1979). This rock type ranges in composition from quartz monzonite to granodiorite, but in general it is granitic-textured, medium crystalline, and composed of abundant plagioclase, potassium feldspar, and quartz, with subordinate hornblende, minor biotite, and accessory magnetite, sphene, apatite, and zircon (table 3). Most plagioclase grains are sericitized to various degrees, and hornblende is commonly altered to chlorite and epidote (Rogers and others, 1979). The southern part of the watershed was mapped to greater detail by Rogers and others (1979) than the northern part (Broedel, 1961); Broedel classified all rocks simply as granodiorite. The greater amount of quartz and lesser amount of plagioclase in the quartz monzonite may make the monzonite more resistant to weathering than the granodiorite, and they may explain why hillslopes underlain by monzonite in the watershed have higher elevation and greater relief that elsewhere in the basin (Larsen, 1997). The quartz monzonite may actually underlie a larger portion of the Cayaguás basin than the reported 11 percent, because this accentuated topography is expressed elsewhere in areas mapped as granodiorite.

Table 3. Mineral content of granitic intrusions, eastern Puerto Rico.

[--, not available]

Mineral	Average mineral content of bedrock (weight percent)		
	Río Blanco[1]	San Lorenzo[2]	Quartz monzonite of Punta Guayanes[2]
Plagioclase	55.8	51	35
Quartz	26.0	20.5	33
Amphibole	7.3	11	1.5
K-feldspar	5.0	11	28
Biotite	3.6	4.5	2
Accessory[3]	1.4	--	--
Apatite	0.2	--	--
Iron oxide	0.7	1.5	0.5
Total	100	99.5	100

[1]Seiders (1971b).

[2]Rogers and others (1979).

[3]Accessory minerals: Río Blanco—epidote, sphene, tourmaline, zircon; San Lorenzo—apatite, sphene, zircon, and minor augite, myrmekite; Punta Guayanes—apatite, sphene, zircon.

The effect of geology on channel morphology in the WEBB watersheds is evident in the bed material and particle size (see cover photograph). Stream channels in the Icacos and Cayaguás watersheds typically have sand-bed channels and floodplains that are dominantly sandy alluvium with occasional boulders. Median grain size (D_{50}) is 0.6 millimeters (mm) and 0.5 mm, respectively, in the two channels (Larsen, 1997). Channels in the Mameyes and Canóvanas watersheds are generally characterized by little to no floodplain and channels lined with bedrock, boulders, or cobbles, with little bed sediment. Median grain size in these two channels is 70 mm and 110 mm, respectively (Larsen, 1997).

Soil and Saprolite

Intense, continuous weathering in the warm, humid-tropical climate of the Luquillo Mountains and the Loíza watershed has produced a mantle of soil overlying both granitic and volcaniclastic bedrock that is as much as 24 m thick (Simon and others, 1990; White and others, 1998). Below the surface-soil horizons, which show strong bioturbation (Brown and others, 1983; Brown and others, 1995; González and others, 1996) and subsoil movement (Lewis, 1974; Larsen and others, 1999), is commonly a layer of saprolite. Saprolite is soil that is derived from bedrock that has been thoroughly decomposed through isovolumetric chemical weathering; it remains in place and retains the appearance of the bedrock structure (American Geological Institute, 1976). The composition of the underlying bedrock, particularly the quartz content, determines the chemical and physical properties of the saprolite (Meyerhoff, 1931; Schellekens and others, 2004; Buss and White, 2012; Stallard, 2012).

Soils in Watersheds Dominated by Volcaniclastic Rock

The volcaniclastic rocks underlying the Mameyes and Canóvanas watersheds are generally quartz poor, and they are composed predominantly of basic feldspars and ferromagnesian minerals (Seiders, 1971a,b,c; Briggs, 1973). In the saprolite, these minerals weather to kaolinite and other clay minerals of the 1:1 lattice type, iron and aluminum oxides, and small amounts of quartz (Huffaker, 2002). Relic grains of plagioclase and mafic minerals are recognizable in some hand specimens of the saprolite (Scatena, 1989). Geoelectric soundings indicate a gradual change from unweathered bedrock to less-weathered saprolite to highly weathered saprolite; active weathering occurs in the less-weathered saprolite (Schellekens and others, 2004). Clay-lined faults and joints, which are common in the saprolite, make primary sedimentary structures difficult to distinguish.

The volcaniclastic saprolite is overlain by clay-rich, quartz-poor soils that are typically 0.8 to 1.0 m deep (Huffaker, 2002). Soils developed on the volcaniclastic rocks are finer grained than those developed on the granitic rocks, and they have lower permeability and infiltration rates than granitic soils (Simon and others, 1990; Murphy and Stallard, 2012). Dense clays in the volcaniclastic soils retard deep infiltration, causing water to follow a shallow trajectory and reach streams quickly (McDowell and others, 1992). Because of the generally high soil moisture content in the Luquillo Mountains, soils are quickly saturated during storms, leading to saturation overflow (Larsen and others, 1999). As such, during periods of intense rainfall, water is commonly observed flowing over the surface in rills and ephemeral gullies.

At the highest elevations in the Mameyes watershed, corresponding with palo colorado forest (see Vegetation and Land Use section), soils overlying the volcaniclastic rock consist primarily of the Yunque clay loam and Moteado clay soils, which are Oxisols, and the Guayabota clay loam and Palm clay soils, which are Inceptisols (Huffaker, 2002). These soils range from poorly drained (on concave slopes) to moderately well drained (on convex slopes). The Inceptisols presumably reflect the greater rainfall in the highest elevations and wetter areas near rivers. At lower elevations, corresponding with tabonuco forest, soils overlying the volcaniclastic rocks consist primarily of Zarzal clay and Cristal clay loam soils, which are Oxisols, and range from somewhat poorly drained (concave slopes) to well drained (convex slopes) (Huffaker, 2002).

The Canóvanas watershed contains a variety of soil types, including Oxisols (Yunque, Moteado, Zarzal, and Cristal clay or clay loams, discussed in the previous paragraph, and the deep, moderately well drained Los Guineos clay), Inceptisols (Mucara silty clay loam and Caguabo clay loam, which are shallow to moderately deep and well drained), Ultisols (Humatas clay and Naranjito silty clay loam, which are deep to moderately deep and well drained), and minor Mollisols (Reilly silty clay loam, found in the floodplain) (Boccheciamp, 1977; Huffaker, 2002). As a result of past agricultural cultivation, much of the original surface layers of several of the soils in the lower part of the Canóvanas watershed, including the Los Guineos, Humatas, Mucara, and Naranjito soils, have been removed by erosion (Boccheciamp, 1977).

Soils in Watersheds Dominated by Granitic Rock

The quartz-rich granitic rocks underlying the Icacos and Cayaguás watersheds weather to a saprolite composed of quartz, weathered biotite, and kaolinite, and other clays and sesquioxides (Boccheciamp, 1978; Murphy and others, 1998; White and others, 1998). Huffaker (2002) contends that the granitic rocks weather more rapidly than the volcanic rocks, and that if other conditions are equal, the regolith overlying the granitic rocks is thicker than that in volcanic areas. The Río Blanco quartz diorite, which underlies the Icacos watershed, has been the subject of extensive studies on chemical weathering rates (including White and Blum, 1995; Dong and others, 1998; Murphy and others, 1998; White and others, 1998; Schulz and White, 1999; Turner and others, 2003; Buss and others, 2005, 2008, 2009; Fletcher and others, 2006; Pett-Ridge and others, 2009; Minyard and others, 2011; Buss and White, 2012). The relatively young age of the Río Blanco quartz diorite, combined with high rainfall and temperature, results in the Icacos watershed having one of the highest documented chemical weathering rates of granitic rocks in the world (White and Blum, 1995; White and others, 1998). The weathering front has been estimated to proceed about 1 centimeter (cm) per 100 years on the basis of cosmogenic evidence (Brown and others, 1995). Stallard (1995) argues that minerals such as intergranular calcite and volatiles in fluid inclusions derived from the late-stage cooling of magma greatly enhance the susceptibility of younger plutons, such as the Río Blanco quartz diorite, to weathering, compared with identical rock types of Precambrian age, where volatiles have migrated out and late-stage minerals have recrystallized. The transition between the quartz-diorite bedrock and saprolite consists of a 20- to 60-cm-thick zone characterized by fracture-bound concentric shells, termed rindlets (Turner and others, 2003; Fletcher and others, 2006; Buss and others, 2008; Buss and White, 2012). The majority of weathering in the watershed occurs in this transition zone, as individual rindlets become progressively more altered away from joint planes. The San Lorenzo granodiorite–quartz diorite, which underlies the Cayaguás watershed, has not been well studied, but because of its similar composition and age it presumably weathers in a comparable manner.

On hillslopes, saprolite is overlain by 0.5–2 m of soil, which is typically sandy and loamy, with a thin, organic-rich A horizon and a layer of translocated clays concentrated in the B horizon (Simon and others, 1990; Huffaker, 2002). Soil thickness on ridges in the Icacos watershed has been observed to be more than ten-fold greater (Simon and others, 1990). Soils on the granitic rocks have higher permeability and infiltration rates than those on the volcaniclastic rocks, allowing greater water infiltration (Simon and others, 1990). The coarse soil is easily eroded and is highly susceptible to landslides when subjected to intensive agricultural activity or other disturbance (Larsen, 2012).

Soils overlying the Río Blanco quartz diorite in the Icacos watershed primarily consist of Picacho and Utuado loamy soils. These Inceptisols are very deep (greater than 150 cm) and somewhat poorly drained (Huffaker, 2002). The Icacos flood plain and low terraces at middle elevations are overlain by the Icacos loam, an Inceptisol which is very deep (greater than 150 cm) and somewhat poorly drained. Quartz persists through the entire profile, becoming more fine grained nearer the surface (Brown and others, 1995).

Soils at the highest elevations in the Cayaguás watershed consist primarily of the Lirios silty clay loam, which is a well-drained Ultisol (Boccheciamp, 1978). Soils at lower elevations primarily consist of the Pandura sandy loam, an Inceptisol. Owing to past agricultural cultivation, both of these soils have lost much of their original surface layers through erosion. By using geomorphic evidence, Larsen and Santiago-Román (2001) estimate that the surface of the Cayaguás basin has been lowered an average of 660 mm since about 1820, comparable to the 500 mm of surface-lowering estimated by using cosmogenic Be^{10} (Brown and others, 1998).

Vegetation and Land Use

All of the natural ecological life zones of Puerto Rico (as developed by Ewel and Whitmore, 1973) are forest (fig. 7). Three life zones dominate the island: subtropical moist forest (58 percent of the main island), subtropical wet forest (23 percent), and subtropical dry forest (18 percent) (Birdsey and Weaver, 1982). Subtropical rain forest, lower montane wet forest, and lower montane rain forest occupy a little more than 1 percent of the island at high elevations, including most of the Mameyes and Icacos watersheds. Historical accounts suggest that, like many other Caribbean islands, Puerto Rico was heavily forested (about 95 percent) prior to European settlement (Wadsworth, 1950; Birdsey and Weaver, 1982). The island's diverse physiography and tropical location result in diverse flora and fauna and a high level of endemism (Gould and others, 2008); however, plant diversity is lower than that at mainland tropical sites (Ashton and others, 2004).

In the 16th century, European settlers began clearing forests for pasture, cropland, timber, and fuel. By 1828, forest covered about 66 percent of Puerto Rico (Wadsworth, 1950). Pressure on land resources increased in the 19th and 20th centuries owing to population growth, expanding production of sugar cane and coffee, economic depression, and the effects of several severe hurricanes. By the late 1940s, forest cover of Puerto Rico had declined to 6 percent; cropland and pasture each accounted for about 42 percent of land cover; the remaining 10 percent contained urban areas and wasteland (Koenig, 1953; Birdsey and Weaver, 1982). During this period, Puerto Rico was one of the most severe1y deforested regions in the world. Soil erosion related to this deforestation released high loads of sediment from hillslopes to footslopes, valley floors,

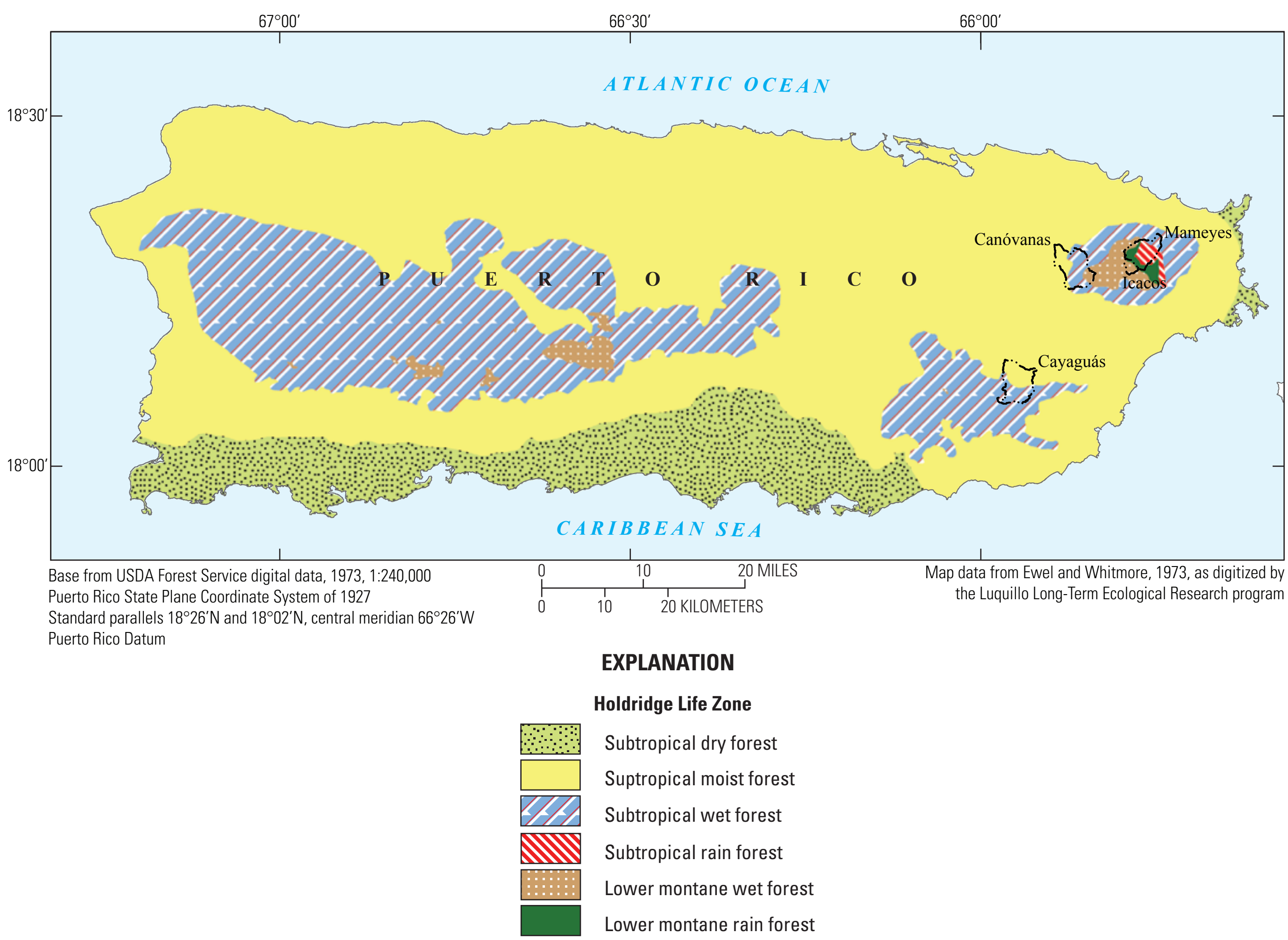

Figure 7. Ecological life zones of Puerto Rico (from Luquillo Long-Term Ecological Research program; digitized from Ewel and Whitmore, 1973).

and streams channels (Larsen, 2012). Much of the remaining forest was in the Luquillo Mountains, because access to this area was limited by steep slopes, high annual rainfall, and its designation as a reserve by the Spanish crown in 1876 and later by the U.S. Government (Zimmerman and others, 1995).

A shift in Puerto Rico's economic base that began in the late 1940s, partly as a result of the U.S. Government's "Operation Bootstrap," led to reforestation (Rudel and others, 2000). In 1934, about 43 percent of the island's gross national product came from agriculture but only 7 percent from industry; by 1996, agriculture and industry contributed 1 percent and 41 percent respectively to the gross national product (López and others, 2001). As Puerto Ricans moved from rural areas to cities on the island or migrated to the United States, agricultural land cover in Puerto Rico declined by 95 percent from 1951 to 2000 (Kennaway and Helmer, 2007). Much of this abandoned land reverted to forest. By 1980, forest cover of Puerto Rico had increased to 31 percent (Franco and others, 1997). In 2003, forest, woodland, and shrubland represented about 44 percent of land area (Gould and others, 2012) (figs. 8 and 9).

Meanwhile, population density of Puerto Rico has increased more than threefold during the last century, resulting in one of the highest densities in the world: more than 400 people/km^2 (López and others, 2001). Puerto Rico now has the highest road density of any Caribbean island, 2.5 km of paved roads per square kilometer (Lugo, 1996). On the basis of population density and remote sensing of developed areas, about 16 percent of the island is considered urban land use, 50 percent is suburban, and 34 percent is rural (Martinuzzi and others, 2007). Eleven percent of the island has developed surface, and about 60 percent of this surface corresponds with high-density development (Martinuzzi and others, 2007). In the San Juan metropolitan area, filling of the mangroves and mudflats has restricted circulation and impaired water quality (Webb and Gómez-Gómez, 1998). Land has been converted to urban uses mostly in lowland regions and on lesser slopes.

Land Cover of Forested Watersheds

The four study watersheds were selected, in part, for differing land cover. The Icacos watershed is almost entirely covered by mature montane wet evergreen forest, which

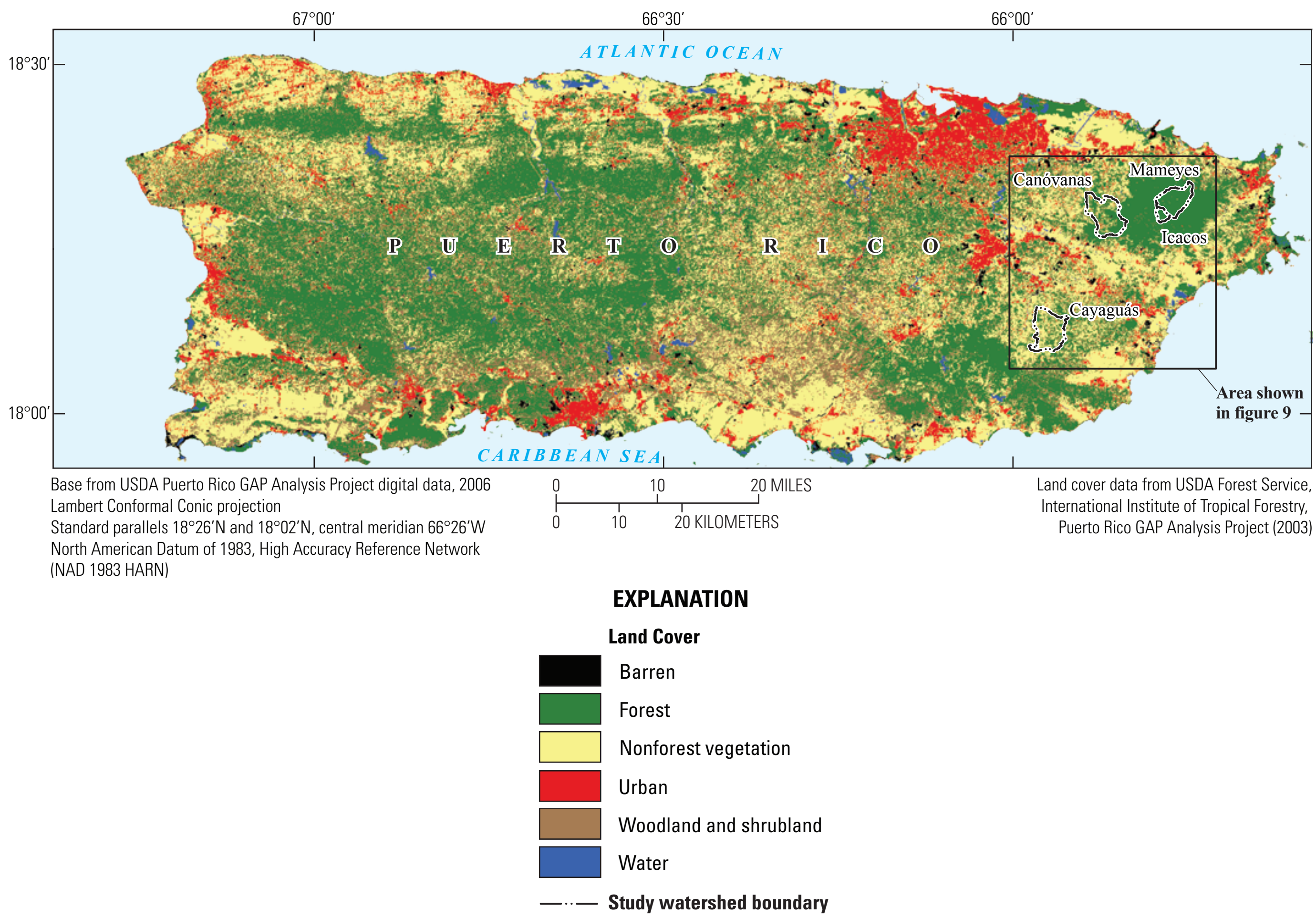

Figure 8. Generalized land cover of Puerto Rico in 2003 (from Gould and others, 2008).

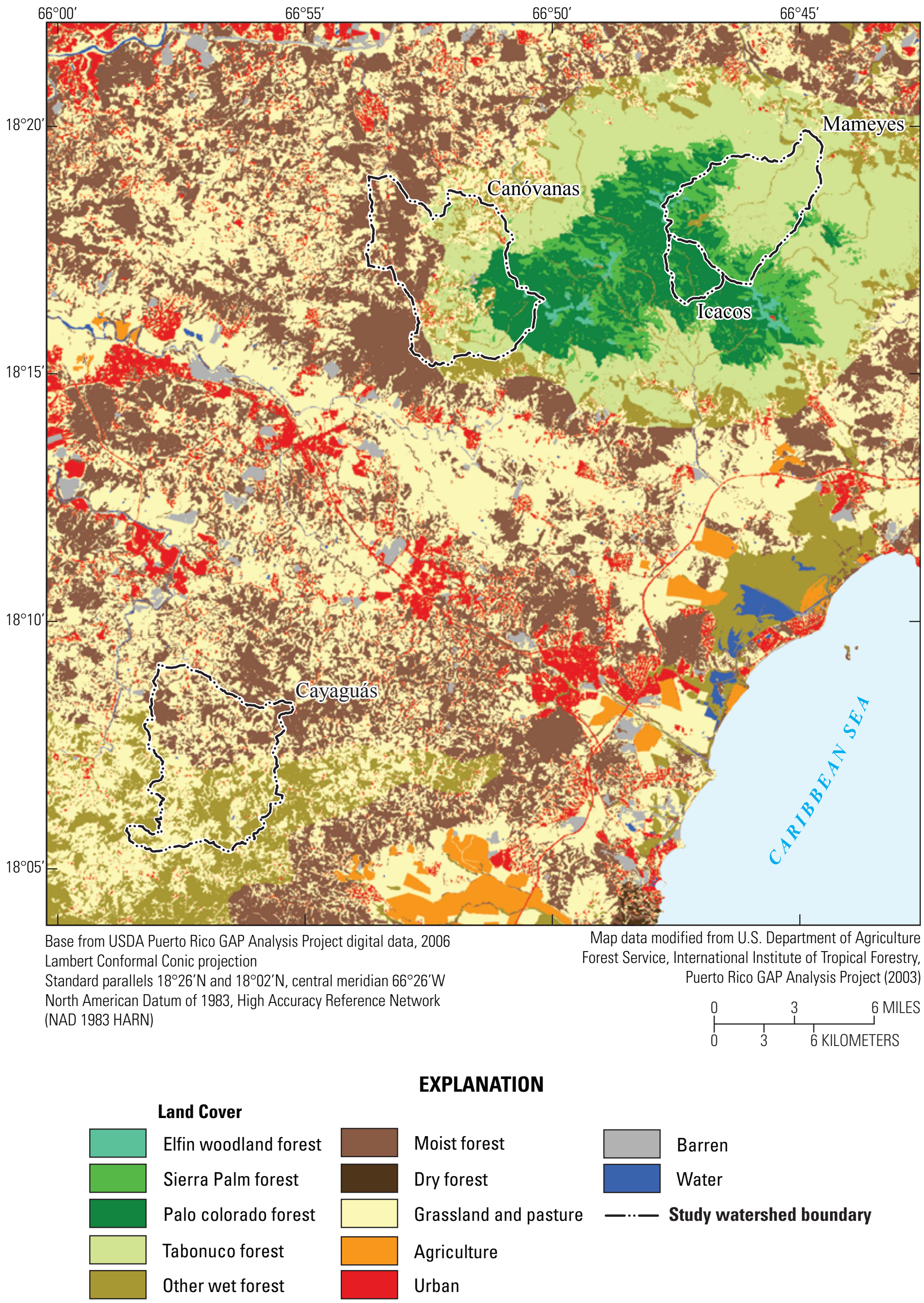

Figure 9. Detailed land cover of study watersheds in 2003 (from Gould and others, 2008).

includes about 85 percent palo colorado forest, 13 percent sierra palm forest, and 2 percent other montane wet forest (Gould and others, 2008) (fig. 9; table 4). Prominent trees are palo colorado (*Cyrilla racemiflora*), caimitillo (*Micropholis garciniaefolia, M. chrysophylloides*), and laurel sabino (*Magnolia splendens*) (Foster and others, 1999). The Mameyes watershed also consists primarily of mature montane wet evergreen forest, but it is larger and has a much greater variation in elevation than the Icacos watershed, and thus it has more varied forest. Land cover is about 57 percent tabonuco forest, 25 percent sierra palm forest, 14 percent palo colorado forest, 1 percent elfin woodland, and 2 percent other montane wet forest (Gould and others, 2008, 2012) (table 4). Above 600 m, vegetation in the Mameyes watershed is primarily palo colorado and sierra palm forest. Elfin woodland, characterized by short, slow-growing vegetation, develops on ridges above 900 m elevation (Weaver, 1986, 1989, 1990). Elevations below 600 m are primarily tabonuco forest. This forest is dominated by the tabonuco tree (*Dacryodes excelsa*), but 170 tree species have been described for this forest type (Foster and others, 1999).

Forest cover in much of the Icacos and Mameyes watersheds persisted during the nadir of forest cover in Puerto Rico in the 1940s, and those watersheds have maintained a continuous forest canopy since that time (table 4). As discussed above, steep topography, harsh conditions, and governmental protection limited access for development or forest conversion. Although the Luquillo Mountains were less affected by development than other areas of Puerto Rico, they are not pristine; cattle production, shade coffee, timber extraction, subsistence farming, and charcoal production were practiced in the late 1800s and in the 1900s, primarily below 600 m elevation. The USDA Forest Service purchased much of the lower-elevation land in the Luquillo Mountains in the 1930s (Zimmerman and others, 1995). Nonnative bamboo was introduced from Asia in the 1930s and 1940s along roads to stabilize slopes; however, during major disturbances such as hurricanes, extensive bamboo root systems can actually help cause catastrophic slope failures (O'Connor and others, 2000). Bamboo is expanding downstream in streams within the Mameyes watershed at a rate of 8 meters per year (O'Connor and others, 2000). Large stands of bamboo are observed in the Mameyes and Icacos watersheds, especially near roads.

Land Cover of Developed Watersheds

In the Canóvanas watershed, land cover is currently about 71 percent forest, 26 percent grassland or pasture, and 3 percent urban (Gould and others, 2008) (table 4). Above 600 m elevation, land cover is primarily palo colorado forest, similar to the Icacos and Mameyes watersheds (fig. 9, table 4). Between 400 and 600 m, land cover is primarily tabonuco forest and grassland or pasture. Below 400 m, land cover is primarily secondary lowland moist forest and grassland or pasture. The Canóvanas watershed has a mixed land-use history. Elevations above 600 m were forested in the middle 20th century, but most of the lower watershed was used for pasture, coffee, and fruit crops, and to a lesser degree, bananas and sugar cane (Kennaway and Helmer, 2007). Between the 1950s and the 1970s, the predominant land cover shifted from agriculture and pasture to forest, and forest cover in the watershed increased by 44 percent (table 4). These decades correspond with a low point in population density of the Cubuy barrio, which is entirely within the Canóvanas watershed and represents the majority of the land area in the watershed (fig. 10). Current population density has returned to that of the 1950s, but land use is predominantly residential as opposed to agricultural (Martinuzzi and others, 2007; Parés-Ramos and others, 2008).

Current land cover in the Cayaguás watershed is 57 percent pasture, 41 percent forest or shrubland (primarily lowland moist forest and montane wet forest) and 2 percent urban (fig. 9, table 4). Fifty years ago, the Cayaguás watershed was almost entirely devoted to agricultural activities, such as pasture, fruit crops, and tobacco (Kennaway and Helmer, 2007). Forest cover has increased about 20 percent since the late 1970s, primarily at the expense of pasture and grasslands (table 4). Population densities in the Quebrada Arenas barrio, which is entirely within the Cayaguás watershed and represents most of the land area in the watershed, reached a low point in the 1980 census (fig. 10). Population has since been rising owing to increased residential land use (Martinuzzi and others, 2007; Parés-Ramos and others, 2008).

Summary

Four watersheds in eastern Puerto Rico have been studied since 1991 as part of the U.S. Geological Survey's Water, Energy, and Biogeochemical Budget program. These watersheds differ in geology, soils, and land cover. The Icacos watershed is underlain by granitic rock, which weathers to quartz- and clay-rich, sandy soils. Land cover is primarily old-growth wet forest, and human disturbance has been minimal. The Mameyes watershed is primarily underlain by volcaniclastic rock, which weathers to quartz-poor, fine-grained soils. This watershed also contains largely old-growth wet forest. The Canóvanas watershed is underlain by volcaniclastic rocks and soils that are similar to those in the Mameyes, but historical agricultural practices at lower elevations have led to substantial erosion of soils. This watershed has largely reforested since the 1950s. The Cayaguás watershed is underlain by granitic rock; this watershed was also historically used for agriculture and has been deeply eroded. It has undergone some reforestation since the 1970s. Past soil erosion in the Canóvanas and Cayaguás watersheds released high loads of sediment from hillslopes to footslopes, valley floors, and streams channels. The reforestation of these watersheds, and of Puerto Rico, may serve as a prototype for the hydrological and chemical response of other tropical areas that are shifting from an agricultural to an industrial economy.

Table 4. Land cover and land-cover dynamics in study watersheds, eastern Puerto Rico.

[Land-cover dynamics are indicated as percentage increase or decrease from 1936, 1950 (Lugo and others, 2004), and 1977 (Ramos and Lugo, 1994) for woody (forest, shrubland, and woodland), herbaceous (grassland, pastures, agriculture), and developed areas. In 1936 and 1950, the Cayaguás watershed was primarily agricultural and nonforested. --, not analyzed]

Land cover type	Icacos				Mameyes				Canóvanas				Cayaguás			
	2003 land cover[1]	Percent change since			2003 land cover	Percent change since			2003 land cover	Percent change since			2003 land cover	Percent change since		
	percent	1936	1950	1977	percent	1936	1950	1977	percent	1936	1950	1977	percent	1936	1950	1977
Woody	99.9	0	0	0	99.6	1	0	0	71.3	47	44	2	41.7	--	--	20
Palo colorado forest	85.4	--	--	--	13.9	--	--	--	14.2	--	--	--	0.00	--	--	--
Sierra palm forest	12.7	--	--	--	25.3	--	--	--	1.60	--	--	--	0.00	--	--	--
Elfin woodland	0.00	--	--	--	1.07	--	--	--	0.38	--	--	--	0.00	--	--	--
Tabonuco forest	0.00	--	--	--	57.0	--	--	--	24.5	--	--	--	0.00	--	--	--
Other montane wet forest, shrubland, woodland	1.84	--	--	--	2.36	--	--	--	10.4	--	--	--	21.5	--	--	--
Lowland moist forest, shrubland, woodland	0.00	--	--	--	0.00	--	--	--	20.2	--	--	--	19.8	--	--	--
Abandoned and active coffee plantations	0.00	--	--	--	0.00	--	--	--	0.00	--	--	--	0.37	--	--	--
Herbaceous	0.15	0	0	0	0.32	–1	0	0	25.68	–41	–48	3	56.7	--	--	–23
Moist grasslands and pastures	0.15	--	--	--	0.32	--	--	--	25.68	--	--	--	56.7	--	--	--
Developed	0.00	0	0	0	0.02	0	0	0	2.79	3	3	–4	1.55	--	--	2
Low-density urban development	0.00	--	--	--	0.02	--	--	--	2.79	--	--	--	1.55	--	--	--
Other	0.00	0	0	0	0.05	0	0	0	0.25	0	0	0	0.08	--	--	0
Barren	0.00	--	--	--	0.04	--	--	--	0.25	--	--	--	0.00	--	--	--
Freshwater	0.00	--	--	--	0.004	--	--	--	0.00	--	--	--	0.08	--	--	--
Total	100				100				100				100			

[1]From Gould and others, 2008.

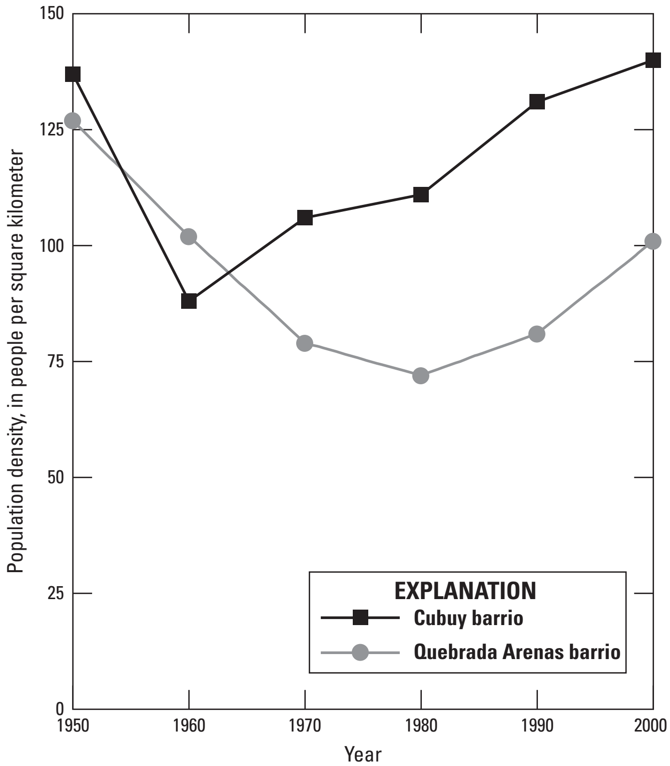

Figure 10. Population density in the Cubuy barrio (in Canóvanas watershed) and the Quebrada Arenas barrio (in Cayaguás watershed) (from U.S. Census, 2000).

Acknowledgments

This chapter was greatly improved by reviews by John F. Walker and Richard M.T. Webb of the U.S. Geological Survey and F.N. Scatena of the University of Pennsylvania.

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